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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventorship..... Jakubowski et al.
Applicant..... Microsoft Corporation
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Title: System and Method for Protecting Digital Goods Using Random and Automatic Code Obfuscation

TRANSMITTAL LETTER AND CERTIFICATE OF MAILING

To: Commissioner of Patents and Trademarks,
Washington, D.C. 20231

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The following enumerated items accompany this transmittal letter and are being submitted for the matter identified in the above caption.

1. Specification—title page, plus 40 pages, including 34 claims and Abstract
2. Transmittal letter including Certificate of Express Mailing
3. 8 Sheets Formal Drawings (Figs. 1-8)
4. Return Post Card

Large Entity Status ☒ [x]

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Date: March 27, 2000

By: L. C. Lee

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

APPLICATION FOR LETTERS PATENT

**System and Method for Protecting Digital Goods Using
Random and Automatic Code Obfuscation**

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ATTORNEY'S DOCKET NO. MS1-515US

TECHNICAL FIELD

This invention relates to systems and methods for protecting digital goods, such as software and content (e.g., audio, video, etc.).

BACKGROUND

Digital goods (e.g., software products, data, content, etc.) are often distributed to consumers via fixed computer readable media, such as a compact disc (CD-ROM), digital versatile disc (DVD), soft magnetic diskette, or hard magnetic disk (e.g., a preloaded hard drive). More recently, more and more content is being delivered in digital form online over private and public networks, such as Intranets and the Internet. Online delivery improves timeliness and convenience for the user, as well as reduces delivery costs for a publisher or developers. Unfortunately, these worthwhile attributes are often outweighed in the minds of the publishers/developers by a corresponding disadvantage that online information delivery makes it relatively easy to obtain pristine digital content and to pirate the content at the expense and harm of the publisher/developer.

The unusual property of content is that the publisher/developer (or reseller) gives or sells the *content* to a client, but continues to restrict *rights* to use the content even after the content is under the sole physical control of the client. For instance, a software developer typically sells a limited license in a software product that permits a user to load and run the software product on one or more machines (depending upon the license terms), as well as make a back up copy. The user is typically not permitted to make unlimited copies or redistribute the software to others. As another example, a content producer typically retains copyright to a work so that the user cannot reproduce or publish the work without

1 permission. The producer may also adjust pricing according to whether the client
2 is allowed to make a persistent copy, or is just allowed to view the content online
3 as it is delivered.

4 These scenarios reveal a peculiar arrangement. The user that possesses the
5 digital bits often does not have full rights to their use; instead, the provider retains
6 at least some of the rights. In a very real sense, the legitimate user of a computer
7 can be an adversary of the data or content provider.

8 One of the on-going concerns with distribution of digital goods is the need
9 to provide "digital rights management" (or "DRM") protection to prevent
10 unauthorized distribution, copying and/or illegal operation, or access to the digital
11 goods. An ideal digital goods distribution system would substantially prevent
12 unauthorized distribution/use of the digital goods. Digital rights management is
13 fast becoming a central requirement if online commerce is to continue its rapid
14 growth. Content providers and the computer industry must quickly address
15 technologies and protocols for ensuring that digital goods are properly handled in
16 accordance with the rights granted by the developer/publisher. If measures are not
17 taken, traditional content providers may be put out of business by widespread theft
18 or, more likely, will refuse altogether to deliver content online.

19 Various DRM techniques have been developed and employed in an attempt
20 to thwart potential pirates from illegally copying or otherwise distributing the
21 digital goods to others. For example, one DRM technique includes requiring the
22 consumer to insert the original CD-ROM or DVD for verification prior to enabling
23 the operation of a related copy of the digital good. Unfortunately, this DRM
24 technique typically places an unwelcome burden on the honest consumer,
25 especially those concerned with speed and productivity. Moreover, such

1 techniques are impracticable for digital goods that are site licensed, such as
2 software products that are licensed for use by several computers, and/or for digital
3 goods that are downloaded directly to a computer. Additionally, it is not overly
4 difficult for unscrupulous individuals/organizations to produce working pirated
5 copies of the CD-ROM.

6 Another DRM technique includes requiring or otherwise encouraging the
7 consumer to register the digital good with the provider, for example, either through
8 the mail or online via the Internet or a direct connection. Thus, the digital good
9 may require the consumer to enter a registration code before allowing the digital
10 good to be fully operational or the digital content to be fully accessed.
11 Unfortunately, such DRM techniques are not always effective since unscrupulous
12 individuals/organizations need only break through or otherwise undermine the
13 DRM protections in a single copy of the digital good. Once broken, copies of the
14 digital good can be illegally distributed, hence such DRM techniques are
15 considered to be Break-Once, Run-Everywhere (BORE) susceptible.

16 Accordingly, there remains a need for a DRM architecture that addresses
17 the concerns of the publisher/developer and protects the digital goods from many
18 of the known and common attacks, but does not impose unnecessary and
19 burdensome requirements on legitimate users.
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1 **SUMMARY**

2 A digital rights management (DRM) distribution architecture produces and
3 distributes digital goods (e.g., software, audio, video, and other content) in a
4 fashion that renders the digital goods resistant to many known forms of attacks.
5 The DRM distribution architecture protects digital goods by automatically and
6 randomly manipulating portions of the code using multiple protection techniques.

7 In one implementation, the architecture includes a production server that
8 produces the protected digital goods from the original digital goods prior to
9 distribution to a client. The production server is equipped with an obfuscation
10 system that attempts to augment the original digital good with protection qualities
11 that are difficult to detect and, if detected, are very difficult to attack.

12 The obfuscation system has a set of multiple protection tools. The
13 obfuscation system automatically parses the original digital good and applies
14 selected protection tools to various portions of the parsed good in a random
15 manner to produce the protected digital good. Applying a mixture of protection
16 techniques in random fashion makes it extremely difficult for pirates to create
17 illicit copies that go undetected as legitimate copies.

18 The obfuscation system also has a quantitative unit to specify a quantity of
19 protection qualities to be added to the digital good. For instance, the quantitative
20 unit may allow a producer to specify how many additional lines of code may be
21 added to the digital good for the purposes of protection, or how many checkpoints
22 are added, or whether runtime may be diminished for the sake of protection.

23 The client is equipped with a secure processor system to execute the
24 protected digital good. As the digital good is executed, it may be evaluated
25

1 according to the different protection schemes to determine whether the digital
2 good is authentic or an illicit copy.

3 4 **BRIEF DESCRIPTION OF THE DRAWINGS**

5 The same numbers are used throughout the drawings to reference like
6 elements and features.

7 Fig. 1 is a block diagram of a DRM distribution architecture that protects
8 digital goods by automatically and randomly obfuscating portions of the goods
9 using various tools.

10 Fig. 2 is a block diagram of a system for producing a protected digital good
11 from an original good.

12 Fig. 3 is a flow diagram of a protection process implemented by the system
13 of Fig. 2.

14 Fig. 4 is a diagrammatical illustration of a digital good after being coded
15 using the process of Fig. 3.

16 Fig. 5 is a diagrammatical illustration of a protected digital good that is
17 shipped to a client, and shows an evaluation flow through the digital good that the
18 client uses to evaluate the authenticity of the good.

19 Fig. 6 is a flow diagram of an oblivious checking process that may be
20 employed by the system of Fig. 2.

21 Fig. 7 is a diagrammatic illustration of a digital good that is modified to
22 support code integrity verification.

23 Fig. 8 is a diagrammatic illustration of a digital good that is modified to
24 support cyclic code integrity verification.

DETAILED DESCRIPTION

A digital rights management (DRM) distribution architecture produces and distributes digital goods in a fashion that renders the digital goods resistant to many known forms of attacks. The DRM distribution architecture protects digital goods by automatically and randomly manipulating portions of the code using multiple protection techniques. Essentially any type of digital good may be protected using this architecture, including such digital goods as software, audio, video, and other content. For discussion purposes, many of the examples are described in the context of software goods, although most of the techniques described herein are effective for non-software digital goods, such as audio data, video data, and other forms of multimedia data.

DRM Distribution Architecture

Fig. 1 shows a DRM distribution architecture 100 in which digital goods (e.g., software, video, audio, etc.) are transformed into protected digital goods and distributed in their protected form. The architecture 100 has a system 102 that develops or otherwise produces the protected good and distributes the protected good to a client 104 via some form of distribution channel 106. The protected digital goods may be distributed in many different ways. For instance, the protected digital goods may be stored on a computer-readable medium 108 (e.g., CD-ROM, DVD, floppy disk, etc.) and physically distributed in some manner, such as conventional vendor channels or mail. The protected goods may alternatively be downloaded over a network (e.g., the Internet) as streaming content or files 110.

1 The developer/producer system 102 has a memory 120 to store an original
2 digital good 122, as well as the protected digital good 124 created from the
3 original digital good. The system 102 also has a production server 130 that
4 transforms the original digital good 122 into the protected digital good 124 that is
5 suitable for distribution. The production server 130 has a processing system 132
6 and implements an obfuscator 134 equipped with a set of multiple protection tools
7 136(1)-136(N). Generally speaking, the obfuscator 134 automatically parses the
8 original digital good 122 and applies selected protection tools 136(1)-136(N) to
9 various portions of the parsed good in a random manner to produce the protected
10 digital good 124. Applying a mixture of protection techniques in random fashion
11 makes it extremely difficult for pirates to create illicit copies that go undetected as
12 legitimate copies.

13 The original digital good 122 represents the software product or data as
14 originally produced, without any protection or code modifications. The protected
15 digital good 124 is a unique version of the software product or data after the
16 various protection schemes have been applied. The protected digital good 124 is
17 functionally equivalent to and derived from the original data good 122, but is
18 modified to prevent potential pirates from illegally copying or otherwise
19 distributing the digital goods to others. In addition, some modifications enable the
20 client to determine whether the product has been tampered with.

21 The developer/producer system 102 is illustrated as a single entity, with
22 memory and processing capabilities, for ease of discussion. In practice, however,
23 the system 102 may be configured as one or more computers that jointly or
24 independently perform the tasks of transforming the original digital good into the
25 protected digital good.

1 The client 104 has a secure processor 140, memory 142 (e.g., RAM, ROM,
2 Flash, hard disk, CD-ROM, etc.), one or more input devices 144 (e.g., keyboard,
3 joystick, voice recognition, etc.), and one or more output devices 146 (e.g.,
4 monitor, speakers, etc.). The client may be implemented as a general purpose
5 computing unit (e.g., desktop PC, laptop, etc.) or as other devices, such as set-top
6 boxes, audio/video appliances, game consoles, and the like.

7 The client 104 runs an operating system 150, which is stored in memory
8 142 and executed on the secure processor 140. Operating system 150 represents
9 any of a wide variety of operating systems, such as a multi-tasking, open platform
10 system (e.g., a "Windows"-brand operating system from Microsoft Corporation).
11 The operating system 150 includes an evaluator 152 that evaluates the protected
12 digital goods prior to their utilization to determine whether the protected digital
13 goods have been tampered with or modified in any manner. In particular, the
14 evaluator 152 is configured to analyze the various portions according to the
15 different protection schemes originally used to encode the good to evaluate the
16 authenticity of the digital good.

17 Some protection schemes involve executing instructions, analyzing data,
18 and performing other tasks in the most secure areas of the operating system 150
19 and secure processor 140. Accordingly, the evaluator 152 includes code portions
20 that may be executed in these most secure areas of the operating system and secure
21 processor. Although the evaluator 152 is illustrated as being integrated into the
22 operating system 150, it may be implemented separately from the operating
23 system.

24 In the event that the client detects some tamper activity, the secure
25 processor 140 acting alone, or together with the operating system 150, may decline

1 to execute the suspect digital code. For instance, the client may determine that the
2 software product is an illicit copy because the evaluations performed by the
3 evaluator 152 are not successful. In this case, the evaluator 152 informs the secure
4 processor 140 and/or the operating system 150 of the suspect code and the secure
5 processor 140 may decline to run that software product.

6 It is further noted that the operating system 150 may itself be the protected
7 digital good. That is, the operating system 150 may be modified with various
8 protection schemes to produce a product that is difficult to copy and redistribute,
9 or at least makes it easy to detect such copying. In this case, the secure processor
10 140 may be configured to detect an improper version of the operating system
11 during the boot process (or at other times) and prevent the operating system from
12 fully or partially executing and obtaining control of system resources.

13 For protected digital goods delivered over a network, the client 104
14 implements a tamper-resistant software (not shown or implemented as part of the
15 operating system 150) to connect to the server 102 using an SSL (secure sockets
16 layer) or other secure and authenticated connection to purchase, store, and utilize
17 the digital good. The digital good may be encrypted using well-known algorithms
18 (e.g., RSA) and compressed using well-known compression techniques (e.g., ZIP,
19 RLE, AVI, MPEG, ASF, WMA, MP3).

20 21 **Obfuscating System**

22 Fig. 2 shows the obfuscator 134 implemented by the production server 130
23 in more detail. The obfuscator 134 is configured to transform an original digital
24 good 122 into a protected digital good 124. The obfuscating process is usually
25 applied just before the digital good is released to manufacture or prior to being

1 downloaded over a network. The process is intended to produce a digital good
2 that is protected from various forms of attacks and illicit copying activities. The
3 obfuscator 134 may be implemented in software (or firmware), or a combination
4 of hardware and software/firmware.

5 The obfuscator 134 has an analyzer 200 that analyzes the original digital
6 good 122 and parses it into multiple segments. The analyzer 200 attempts to
7 intelligently segment the digital good along natural boundaries inherent in the
8 product. For instance, for a software product, the analyzer 200 may parse the code
9 according to logical groupings of instructions, such as routines, or sub-routines, or
10 instruction sets. Digital goods such as audio or video products may be parsed
11 according to natural breaks in the data (e.g., between songs or scenes), or at
12 statistically computed or periodic junctures in the data.

13 In one specific implementation for analyzing software code, the analyzer
14 200 may be configured as a software flow analysis tool that converts the software
15 program into a corresponding flow graph. The flow graph is partitioned into many
16 clusters of nodes. The segments may then take the form of sets of one or more
17 nodes in the flow graph. For more information on this technique, the reader is
18 directed to co-pending U.S. Patent Application Serial Number _____, entitled "A
19 Technique for Producing, Through Watermarking, Highly Tamper-Resistant
20 Executable Code and Resulting "Watermarked" Code So Formed", which was
21 filed March 14, 2000, in the names of Ramarathnam Venkatesan and Vijay
22 Vazirani. This Application is assigned to Microsoft Corporation and is hereby
23 incorporated by reference.
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1 The segments may overlap one another. For instance, one segment may
2 contain a set of instructions in a software program and another segment may
3 contain a subset of the instructions, or contain some but not all of the instructions.

4 The obfuscator 134 also has a target segment selector 202 that randomly
5 applies various forms of protection to the segmented digital good. In the
6 illustrated implementation, the target selector 202 implements a pseudo random
7 generator (PRG) 204 that provides randomness in selecting various segments of
8 the digital good to protect. The target segment selector 202 works together with a
9 tool selector 206, which selects various tools 136 to augment the selected
10 segments for protection purposes. In one implementation, the tool selector 206
11 may also implement a pseudo random generator (PRG) 208 that provides
12 randomness in choosing the tools 136.

13 The tools 136 represent different schemes for protecting digital products.
14 Some of the tools 136 are conventional, while others are not. These distinctions
15 will be noted and emphasized throughout the continuing discussion. Fig. 2 shows
16 sixteen different tools or schemes that create a version of a digital good that is
17 difficult to copy and redistribute without detection and that is resistant to many of
18 the known pirate attacks, such as BORE (break once, run everywhere) attacks and
19 disassembly attacks.

20 The illustrated tools include oblivious checking 136(1), code integrity
21 verification 136(2), acyclic and cyclic code integrity verification 136(3), secret
22 key scattering 136(4), obfuscated function execution 136(5), code as an S-box
23 136(6), encryption/decryption 136(7), probabilistic checking 136(8), Boolean
24 check obfuscation 136(9), in-lining 136(10), reseeding of PRG with time varying
25 inputs 136(11), anti-disassembly methods 136(12), shadowing of relocatable

addresses 136(13), varying execution paths between runs 136(14), anti-debugging methods 136(15), and time/space separation between tamper detection and response 136(16). The tools 136(1)-136(16) are examples of possible protection techniques that may be implemented by the obfuscator 134. It is noted that more or less than the tools may be implemented, as well as other tools not mentioned or illustrated in Fig. 2. The exemplary tools 136(1)-136(16) are described below in more detail beneath the heading "Exemplary Protection Tools".

The target segment selector 202 and the tool selector 206 work together to apply various protection tools 136 to the original digital good 122 to produce the protected digital good 124. For segments of the digital good selected by the target segment selector 202 (randomly or otherwise), the tool selector 206 chooses various protection tools 136(1)-136(16) to augment the segments. In this manner, the obfuscator automatically applies a mixture of protection techniques in a random manner that makes it extremely difficult for pirates to create usable versions that would not be detectable as illicit copies.

The obfuscator 134 also includes a segment reassembler 210 that reassembles the digital good from the protected and non-protected segments. The reassembler 210 outputs the protected digital good 124 that is ready for mass production and/or distribution.

The obfuscator 134 may further be configured with a quantitative unit 212 that enables a producer/developer to define how much protection should be applied to the digital good. For instance, the producer/developer might request that any protection not increase the runtime of the product. The producer/developer may also elect to set the number of checkpoints (e.g., 500 or 1000) added to the digital good as a result of the protection, or define a maximum

1 number of lines/bytes of code that are added for protection purposes. The
2 quantitative unit 212 may include a user interface (not shown) that allows the user
3 to enter parameters defining a quantitative amount of protection.

4 The quantitative unit 212 provides control information to the analyzer 200,
5 target segment selector 202, and tool selector 206 to ensure that these components
6 satisfy the specified quantitative requirements. Suppose, for example, the
7 producer/developer enters a predefined number of checkpoints (e.g., 500). With
8 this parameter, the analyzer 200 ensures that there are a sufficient number of
9 segments (e.g., >500), and the target segment selector 202 and tool selector 206
10 apply various tools to different segments such that the resulting number of
11 checkpoints approximates 500.

12 13 **General Operation**

14 Fig. 3 shows the obfuscation process 300 implemented by the obfuscator
15 134 at the production server 102. The obfuscation process is implemented in
16 software and will be described with additional reference to Figs. 1 and 2.

17 At block 302, the quantitative unit 212 enables the developer/producer to
18 enter quantitative requirements regarding how much protection should be applied
19 to the digital good. The developer/producer might specify, for example, how
20 many checkpoints are to be added, or how many additional lines of code, or
21 whether runtime can be increased as a result of the added protection.

22 At block 304, the analyzer/parser 200 analyzes an original digital good and
23 parses it into plural segments. The encoded parts may partially or fully overlap
24 with other encoded parts.
25

1 The target segment selector 202 chooses one or more segments (block 306).
2 Selection of the segment may be random with the aid of the pseudo random
3 generator 204. At block 308, the tool selector 206 selects one of the tools 136(1)-
4 136(16) to apply to the selected section. Selection of the tools may also be a
5 randomized process, with the assistance of the pseudo random generator 208.

6 To illustrate this dual selection process, suppose the segment selector 202
7 chooses a set of instructions in a software product. The tool selector 206 may then
8 use a tool that codes, manipulates or otherwise modifies the selected segment.
9 The code integrity verification tool 136(2), for example, places labels around the
10 one or more segments to define the target segment. The tool then computes a
11 checksum of the bytes in the target segment and hides the resultant checksum
12 elsewhere in the digital good. The hidden checksum may be used later by tools in
13 the client 104 to determine whether the defined target segment has been tampered
14 with.

15 Many of the tools 136 place checkpoints in the digital good that, when
16 executed at the client, invoke utilities that analyze the segments for possible
17 tampering. The code verification tool 136(2) is one example of a tool that inserts a
18 checkpoint (i.e., in the form of a function call) in the digital good outside of the
19 target segment. For such tools, the obfuscation process 300 includes an optional
20 block 310 in which the checkpoint is embedded in the digital good, but outside of
21 the target segment. In this manner, the checkpoints for invoking the verification
22 checks are distributed throughout the digital good. In addition, placement of the
23 checkpoints throughout the digital good may be random.

24 The process of selecting segment(s) and augmenting them using various
25 protection tools is repeated for many more segments, as indicated by block 312.

1 Once the obfuscator has finished manipulating the segments of the digital code
2 (i.e., the “no” branch from block 312), the reassembler 210 reassembles the
3 protected and non-protected segments into the protected digital good (block 314).

4 Fig. 4 shows a portion of the protected digital good 124 having segments i ,
5 $i+1$, $i+2$, $i+3$, $i+4$, $i+5$, and so forth. Some of the segments have been augmented
6 using different protection schemes. For instance, segment $i+1$ is protected using
7 tool 7. The checkpoint CP_{i+1} for this segment is located in segment $i+4$.
8 Similarly, segment $i+3$ is protected using tool 3, and the checkpoint CP_{i+3} for this
9 segment is located in segment $i+2$. Segment $i+4$ is protected using tool K , and the
10 checkpoint CP_{i+4} for this segment is located in segment i .

11 Notice that the segments may overlap one another. In this example,
12 segment $i+3$ and $i+4$ partially overlap, thus sharing common data or instructions.
13 Although not illustrated, two or more segments may also completely overlap,
14 wherein one segment is encompassed entirely within another segment. In such
15 situations, a first protection tool is applied to one segment, and then a second
16 protection tool is applied to another segment, which includes data and/or
17 instructions just modified by the first protection tool.

18 Notice also that not all of the segments are necessarily protected. For
19 instance, segment $i+2$ is left “unprotected” in the sense that no tool is applied to
20 the data or instructions in that segment.

21 Fig. 5 shows the protected digital good 124 as shipped to the client, and
22 illustrates control flow through the good as the client-side evaluator 152 evaluates
23 the good 124 for any sign of tampering. The protected digital good 124 has
24 multiple checkpoints 500(1), 500(2),..., 500(N) randomly spread throughout the
25 good. When executing the digital good 124, the evaluator 152 passes through the

1 various checkpoints 500(1)-500(N) to determine whether the checks are valid,
2 thereby verifying the authenticity of the protected digital good.

3 If any checkpoint fails, the client is alerted that the digital good may not be
4 authentic. In this case, the client may refuse to execute the digital good or disable
5 portions of the good in such a manner that renders it relatively useless to the user.

6 7 Exemplary Protection Tools

8 The obfuscator 134 illustrated in Fig. 2 shows sixteen protection tools
9 136(1)-136(16) that may be used to protect the digital good in some manner. The
10 tools are typically invoked after the parser 200 has parsed the digital good into
11 multiple segments. Selected tools are applied to selected segments so that when
12 the segment good is reassembled, the resulting protected digital good is a
13 composite of variously protected segments that are extremely difficult to attack.
14 The sixteen exemplary tools are described below in greater detail.

15 16 Oblivious Checking

17 One tool for making a digital good more difficult to attack is referred to as
18 "oblivious checking". This tool performs checksums on bytes of the digital
19 product without actually reading the bytes.

20 More specifically, the oblivious checking tool is designed so that, given a
21 function f , the tool computes a checksum $S(f)$ such that:

- 22
23 (1) If f is not changed, $S(f)$ can be verified to be correct.
24 (2) If f is changed to f' , $S(f')$ $S(f)$ with extremely high probability.
25

Fig. 6 illustrates an exemplary implementation of an oblivious checking process 600 implemented by the oblivious checking tool 136(1) in the obfuscator 134. The first few blocks 602-606 are directed toward instrumenting the code for function *f*. At block 602, the tool identifies instructions in the software code that possibly modify registers or flags. These instructions are called “key instructions”.

For each key instruction, the tool inserts an extra instruction that modifies a register *R* in a deterministic fashion based on the key instruction (block 604). This extra instruction is placed anywhere in the code, but with the requirement that it is always executed if the corresponding key instruction is executed, and moreover, is always executed after the key instruction. The control flow of function *f* is maintained as originally designed, and does not change. Thus, after instrumenting the code, each valid computation path of function *f* is expected to have instructions modifying *R* in various ways.

At block 606, the tool derives an input set “*I*” containing inputs *x* to the function *f*, which can be denoted by $I = \{x_1, x_2, x_3, \dots, x_n\}$. The input set “*I*” may be derived as a set of input patterns to function *f* that ensures that most or all of the valid computation paths are taken. Such input patterns may be obtained from profile data that provides information about typical runs of the entire program. The input set “*I*” may be exponential in the number of branches in the function, but should not be too large a number.

At block 608, the tool computes *S(f)* through the use of a mapping function *g*, which maps the contents of register *R* to a random element of *I* with uniform probability. Let *f(x)* denote the value of register *R*, starting with 0, after executing *f* on input *x*. The function *f(x)* may be configured to be sensitive to key features of

1 the function so that if a computation path were executed during checksum
2 computation, then any significant change in it would be reflected in $f(x)$ with high
3 probability.

4 One implementation of computing checksum $S(f)$ is as follows:

```
5       Start with  $x = x_0$   
6       Cks :=  $f(x_0)$  XOR  $x_0$   
7       For  $i=1$  to  $K$  do  
8            $x_i := g(f(x_{i-1}))$   
9           Cks +=  $f(x_i)$  XOR  $x_i$ .  
10      End for
```

11 The resulting checksum $S(f)$ is the initial value x_0 , along with the value
12 Cks, or (x_0, Cks) . Notice that the output of one iteration is used to compute the
13 input of the next iteration. This loop makes the checksum shorter, since there is
14 only one initial input instead of a set of K independent inputs.

15 Each iteration of the loop traverses some computation path of the function
16 f . Preferably, each computation path of function f has the same probability of
17 being examined during one iteration. For K iterations, the probability of a
18 particular path being examined is:

$$1 - (1 - 1/n)^k \quad k/n, \text{ where } n = \text{card}(I).$$

21 Code Integrity Verification

22 Another tool for embedding some protection into a digital good is known as
23 “code integrity verification”. This tool defines one or more segments of the digital
24 good with “begin” and “end” labels. Each pair of labels is assigned an
25

1 identification tag. The tool computes a checksum of the data bytes located
2 between the begin and end labels and then hides the checksum somewhere in the
3 digital good.

4 Fig. 7 shows a portion of a digital good 700 having two segments S1 and
5 S2. In the illustration, the two segments partially overlap, although other
6 segments encoded using this tool may not overlap at all. The first segment S1 is
7 identified by begin and end labels assigned with an identification tag ID1, or
8 Begin(ID1) and End(ID1). The second segment S2 is identified by begin and end
9 labels assigned with an identification tag ID2, or Begin(ID2) and End(ID2).

10 The code integrity verification tool computes a checksum of the data bytes
11 between respective pairs of begin/end labels and stores the checksum in the digital
12 good. In this example, the checksums CS1 and CS2 are stored in locations that are
13 separate from the checkpoints.

14 The tool inserts a checkpoint somewhere in the digital good, outside of the
15 segment(s). Fig. 7 illustrates two checkpoints CP1 and CP2 for the associated
16 segments S1 and S2, respectively. Each checkpoint contains a function call to a
17 verification function that, when executed, computes a checksum of the
18 corresponding segment and compares that result with the precomputed checksum
19 hidden in the digital good. The checkpoints therefore have knowledge of where
20 the precomputed checksums are located. In practice, the precomputed checksums
21 CS1 and CS2 may be located at the checkpoints, or separately from the
22 checkpoints as illustrated.

23 When the client executes the digital good, the client-side evaluator 152
24 comes across the checkpoint and calls the verification function. If the checksums
25

1 match, the digital good is assumed to be authentic; otherwise, the client is alerted
2 that the digital good is not authentic and may be an illicit copy.

3 4 Acyclic (Dag-Based) Code Integrity Verification

5 Acyclic, or dag-based, code integrity verification is a tool that is rooted in
6 the code integrity verification, but accommodates more complex nesting among
7 the variously protected segments. “Dag” stands for “directed acyclic graph”.
8 Generally speaking, acyclic code integrity verification imposes an order to which
9 the various checkpoints and checksum computations are performed to
10 accommodate the complex nesting of protected segments.

11 Fig. 8 shows a portion of a digital good 800 having one segment S4
12 completely contained within another segment S3. The checkpoint CP4 for
13 segment S4 is also contained within segment S3. In this nesting arrangement,
14 executing checkpoint CP4 affects the bytes within the segment S3, which in turn
15 affects an eventual checksum operation performed by checkpoint CP3.
16 Accordingly, evaluation of segment S3 is dependent on a previous evaluation of
17 segment S4.

18 The acyclic code integrity verification tool 136(2) attempts to arrange the
19 numerous evaluations in an order that handles all of the dependencies. The tool
20 employs a topological sort to place the checkpoints in a linear order to ensure that
21 dependencies are handled in an orderly fashion.

22 23 Cyclic Code Integrity Verification

24 Cyclic code-integrity verification extends dag-based verification by
25 allowing cycles in the cross-verification graph. For example, if code segment S4

1 verifies code segment S5, and S5 also verifies S4, we have a cycle consisting of
2 the nodes S4 and S5. With such cycles, a proper order for checksum computation
3 does not exist. Thus, a topological sort does not suffice, and some checksums may
4 be computed incorrectly. Cycles require an additional step to fix up any affected
5 checksums.

6 One specific method of correcting checksums is to set aside and use some
7 “free” space inside protected segments. This space, typically one or a few
8 machine words, is part of the code bytes verified by checksum computation. If a
9 particular checksum is incorrect, the extra words can be changed until the
10 checksum becomes proper. While cryptographic hash functions are specifically
11 designed to make this impractical, we can use certain cryptographic message
12 authentication codes (MACs) as checksums to achieve this easily.

13 14 Secret Key Scattering

15 Secret key scattering is a tool that may be used to offer some security to a
16 digital good. Cryptographic keys are often used by cryptography functions to
17 code portions of a digital product. The tool scatters these cryptographic keys, in
18 whole or in part, throughout the digital good in a manner that appears random and
19 untraceable, but still allows the evaluator to recover the keys. For example, a
20 scattered key might correspond to a short string used to compute indices into a
21 pseudorandom array of bytes in the code section, to retrieve the bytes specified by
22 the indices, and to combine these bytes into the actual key.

23 There are two types of secret key scattering methods: static and dynamic.
24 Static key scattering methods place predefined keys throughout the digital good
25 and associate those keys in some manner. One static key scattering technique is to

1 link the scattered keys or secret data as a linked list, so that each key references a
2 next key and a previous or beginning key. Another static key scattering technique
3 is subset sum, where the secret key is converted into an encrypted secret data and a
4 subset sum set containing a random sequence of bytes. Each byte in the secret
5 data is referenced in the subset sum set. These static key scattering techniques are
6 well known in the art.

7 Dynamic key scattering methods break the secret keys into multiple parts
8 and then scatter those parts throughout the digital good. In this manner, the entire
9 key is never computed or stored in full anywhere on the digital good. For
10 instance, suppose that the digital good is encrypted using the well-known RSA
11 public key scheme. RSA (an acronym for the founders of the algorithm) utilizes a
12 pair of keys, including a public key e and a private key d . To encrypt and decrypt
13 a message m , the RSA algorithm requires:

$$15 \quad \text{Encrypt: } y = m^e \bmod n$$

$$16 \quad \text{Decrypt: } y^d = (m^e)^d \bmod n = m$$

17
18 The secret key d is broken into many parts:

$$20 \quad d = d_1 + d_2 + \dots + d_k$$

21
22 The key parts d_1, d_2, \dots, d_k are scattered throughout the digital good. To
23 recover the message during decryption, the client computes:

$$25 \quad y^{d_1} = z_1$$

$$y^d_2 = z_2$$

:

$$y^d_k = z_k$$

where, $m = z_1 \cdot z_2 \cdot \dots z_k$

Obfuscated Function Execution

Another tool that may be used to protect a digital good is known as “obfuscated function execution”. This tool subdivides a function into multiple blocks, which are separately encrypted by the secure processor. When executing the function, the secure processor uses multiple threads to decrypt each block into a random memory area while executing another block concurrently. More specifically, a first process thread decrypts the next block and temporarily stores the decrypted block in memory. Simultaneously, a second process thread executes and then destroys the code in the current block.

The benefit of this tool is that only one block is visible at a time, while the other blocks remain encrypted. On the Intel x86 platform, code run in this manner should be self-relocatable, which means that function calls are typically replaced with calls via function pointers, or an additional program step fixes up any function calls that use relative addressing. Other platforms may have other requirements.

Code As An S-Box

Many ciphers, including the Data Encryption Standard (DES), use several substitution boxes (S-boxes) to scramble data. An S-box is essentially a table that

1 maps n -bit binary strings onto a set of m -bit binary strings, where m and n are
2 small integers. Depending on the cipher, S-boxes may be fixed or variable. Both
3 S-boxes and code segments can be viewed simply as arrays of bytes, so an
4 important code segment can be used as an S-box for a cipher to encrypt another
5 important segment. If a cracker patches the segment serving as the S-box, the
6 encrypted segment will be incorrectly decrypted. This is similar in spirit to using
7 a segment's checksum as the decryption key for another segment, but is subtler
8 and better obfuscated.

10 Encryption/Decryption

11 Another tool to protect a digital good is encryption and decryption. This
12 tool breaks the digital good into different chunks and then encrypts each chunk
13 using different keys. The chunks might represent multi-layered and overlapping
14 code sections. Checksums of code sections can serve as encryption keys.

16 Probabilistic Checking

17 The secure processor has its own pseudorandom-number generator (PRNG)
18 that can be used to perform security actions, such as integrity verification, with
19 certain probabilities. Probabilistic checking uses these probabilities to ensure that
20 a protected program behaves differently during each run. For example, some
21 checks could be during every run, others approximately every other run, and still
22 others only occasionally. This makes the cracker's task much more difficult, since
23 a program no longer exhibits definite, repeatable behavior between runs. In fact, a
24 patched program may work properly once or twice, leading the cracker to believe
25 that his efforts were successful; however, the program will fail in a subsequent

1 run. This is part of an overall strategy of varying paths of execution between runs
2 to complicate reverse engineering, as described elsewhere in this document. .
3

4 Boolean Check Obfuscation

5 Boolean checking utilizes Boolean functions to evaluate the authenticity of
6 code sections or results generated from executing the code. A problem with
7 Boolean checking is that an attacker can often identify the Boolean function and
8 rewrite the code to avoid the Boolean check. According, the Boolean check
9 obfuscation tool attempts to hide the Boolean function so that it is difficult to
10 detect and even more difficult to remove.

11 Consider, for example, the following Boolean check that compares a
12 register with a value “1” as a way to determine whether the digital good is
13 authentic or a copy.

```
14 COMP reg1, 1  
15 BEQ good_guy  
16 (crash)  
17  
18 good_guy (go on)
```

19 In this example, if the compare operation is true (i.e., the Boolean check is
20 valid), the program is to branch to “good_guy” and continue. If the compare is
21 false, the program runs instructions that halt operation. To defeat this Boolean
22 check, an attacker merely has to change the “branch equal” or “BEQ” operation to
23 a “branch always” condition, thereby always directing program flow around the
24 “crash” instructions.
25

1 There are many ways to obfuscate a Boolean check. One approach is to
2 add functions that manipulate the register values being used in the check. For
3 instance, the following operations could be added to the above set of instructions:

```
4           SUB reg1, 1  
5           ADD sp, reg1  
6           :  
7           COMP reg1, 1
```

8 These instructions change the contents of register 1. If an attacker alters the
9 program, there is a likelihood that such changes will disrupt what values are used
10 to change the register contents, thereby causing the Boolean check to fail.

11 Another approach is to add “dummy” instructions to the code. Consider the
12 following:

```
13           LEA reg2, good_guy  
14           SUB reg2, reg1  
15           INC reg2  
16           JMP reg2
```

17 The “subtract”, “increment”, and “jump” instructions following the “load
18 effective address” are dummy instructions that are essentially meaningless to the
19 operation of the code.

20 A third approach is to employ jump tables, as follows:

```
21           MOV reg2, JMP_TAB[reg1]  
22           JMP reg2  
23           JMP_TAB: <bad_guy jump>  
24                    <good_guy jump>
```

1 The above approaches are merely a few of the many different ways to
2 obfuscate Boolean checks. Others may also be used.

3 4 In-Lining

5 The in-lining tool is useful to guard against single points of attack. The
6 secure processor provides macros for inline integrity checks and pseudorandom
7 generators. These macros essentially duplicate code, adding minor variations,
8 which make it difficult to attack.

9 10 Reseeding of PRG With Time Varying Inputs

11 Many software products are designed to utilize random bit streams output
12 by pseudo random number generators (PRGs). PRGs are seeded with a set of bits
13 that are typically collected from multiple different sources, so that the seed itself
14 approximates random behavior. One tool to make the software product more
15 difficult to attack is to reseed the PRGs after every run with time varying inputs so
16 that each pass has different PRG outputs.

17 18 Anti-Disassembly Methods

19 Disassembly is an attack methodology in which the attacker studies a print
20 out of the software program and attempts to discover hidden protection schemes,
21 such as code integrity verification, Boolean check obfuscation, and the like. Anti-
22 disassembly methods try to thwart a disassembly attack by manipulating the code
23 in such a manner that it appears correct and legitimate, but in reality includes
24 information that does not form part of the executed code.

1 One exemplary anti-disassembly method is to employ almost plaintext
2 encryption that indiscreetly adds bits to the code (e.g., changing occasional
3 opcodes). The added bits are difficult to detect, thereby making disassembly look
4 plausible. However, the added disinformation renders the printout not entirely
5 correct, rendering the disassembly practices inaccurate.

6 Another disassembly technique is to add random bytes into code segments
7 and bypass them with jumps. This serves to confuse conventional straight-line
8 disassemblers.

9 10 Shadowing

11 Another protection tool shadows relocatable addresses by adding “secret”
12 constants. This serves to deflect attention away from crucial code sections, such
13 as verification and encryption functions, that refer to address ranges within the
14 executing code. Addition of constants (within a certain range) to relocatable
15 words ensures that the loader still properly fixes up these words if an executable
16 happens not to load at its preferred address. This particular technique is specific to
17 the Intel x86 platform, but variants are applicable to other platforms.

18 19 Varying Execution Path Between Runs

20 One protection tool that may be employed to help thwart attackers is to
21 alter the path of execution through the software product for different runs. As an
22 example, the code may include operations that change depending on the day of
23 week or hour of the day. As the changes are made, the software product executes
24 differently, even though it is performing essentially the same functions. Varying
25

1 the execution path makes it difficult for an attacker to glean clues from repeatedly
2 executing the product.

3 4 Anti-Debugging Methods

5 Anti-debugging methods are another tool that can be used to protect a
6 digital good. Anti-debugging methods are very specific to particular
7 implementations of the digital good, as well as the processor that the good is
8 anticipated to run on.

9 As an example, the client-side secure processor may be configured to
10 provide kernel-mode device drivers (e.g., a WDM driver for Windows NT and
11 2000, and a VxD for Windows 9x) that can redirect debugging-interrupt vectors
12 and change the x86 processor's debug address registers. This redirection makes it
13 difficult for attackers who use kernel debugging products, such as SoftICE.
14 Additionally, the secure processor provides several system-specific methods of
15 detecting Win32-API-based debuggers. Generic debugger-detection methods
16 include integrity verification (to check for inserted breakpoints) and time analysis
17 (to verify that execution takes an expected amount of time).

18 19 Separation in Time/Space of Tamper Detection and Response

20 Another tool that is effective for protecting digital goods is to separate the
21 events of tamper detection and the eventual response. Separating detection and
22 response makes it difficult for an attacker to discern what event or instruction set
23 triggered the response.

24 These events may be separated in time, whereby tamper detection is
25 detected at a first time and a response (e.g., halting execution of the product) is

1 applied at some subsequent time. The events may also be separated in space,
2 meaning that the detection and response are separated in the product itself.

3 4 **Conclusion**

5 Although the description above uses language that is specific to structural
6 features and/or methodological acts, it is to be understood that the invention
7 defined in the appended claims is not limited to the specific features or acts
8 described. Rather, the specific features and acts are disclosed as exemplary forms
9 of implementing the invention.
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CLAIMS

1. A method comprising:
receiving an original digital good; and
randomly applying various forms of protection to the original digital good
to produce a protected digital good.

2. A method as recited in claim 1, wherein the randomly applying
comprises pseudo randomly applying the various forms of protection according to
pseudo random techniques.

3. A method as recited in claim 1, wherein the applying comprises
randomly selecting the forms of protection from a set of available forms of
protection.

4. A method as recited in claim 1, wherein the applying comprises
applying the various forms of protection to randomly selected portions of the
original digital good.

1 5. A method as recited in claim 1, wherein the various forms of
2 protection are selected from a group of protection tools comprising code integrity
3 verification, acyclic code integrity verification, cyclic code integrity verification,
4 secret key scattering, obfuscated function execution, encryption/decryption,
5 probabilistic checking, Boolean check obfuscation, in-lining, reseeding pseudo
6 random number generators with time varying inputs, anti-disassembly methods,
7 varying execution paths between runs, anti-debugging methods, and time/space
8 separation between tamper detection and response.

9
10 6. A method as recited in claim 1, wherein the applying comprises
11 applying a form of protection in which a checksum can be computed on a set of
12 bytes of the digital good without actually reading the bytes.

13
14 7. A computer-readable medium comprising computer-readable
15 instructions that, when executed by a processor, direct a computer system to
16 perform the method as recited in claim 1.

17
18 8. A method comprising:
19 segmenting a digital good into a plurality of segments;
20 selecting multiple segments from the plurality of segments; and
21 transforming the selected segments according to different protection
22 techniques to produce a protected digital good having a composite of variously
23 protected segments.

1 **9.** A method as recited in claim 8, wherein at least two of the segments
2 overlap one another.

3
4 **10.** A method as recited in claim 8, wherein the selecting comprises
5 randomly selecting the segments.

6
7 **11.** A method as recited in claim 8, wherein the transforming comprises
8 transforming the selected segments according to randomly chosen protection
9 techniques.

10
11 **12.** A method as recited in claim 8, wherein the transforming comprises:
12 augmenting at least one segment using a certain protection technique; and
13 inserting a checkpoint, which may be used to evaluate a validity of the
14 augmented segment, within the protected digital good but outside of the
15 augmented segment being evaluated.

16
17 **13.** A method as recited in claim 8, further comprising receiving
18 quantitative parameters indicative of how much the protected digital good should
19 be altered.

20
21 **14.** A method as recited in claim 13, wherein the transforming is
22 performed to satisfy the quantitative parameters.

1 **15.** A method as recited in claim 8, wherein the protection techniques
2 are selected from a group of protection tools comprising code integrity
3 verification, acyclic code integrity verification, cyclic code integrity verification,
4 secret key scattering, obfuscated function execution, encryption/decryption,
5 probabilistic checking, Boolean check obfuscation, in-lining, reseeding pseudo
6 random number generators with time varying inputs, anti-disassembly methods,
7 varying execution paths between runs, anti-debugging methods, and time/space
8 separation between tamper detection and response.

9
10 **16.** A method as recited in claim 8, wherein the transforming comprises
11 applying a protection technique in which a checksum can be computed on a set of
12 bytes of the digital good without actually reading the bytes.

13
14 **17.** A computer-readable medium comprising computer-readable
15 instructions that, when executed by a processor, direct a computer system to
16 perform the method as recited in claim 8.

17
18 **18.** A method comprising:
19 establishing parameters prescribing a desired quantity of protection to be
20 applied to a software product;
21 parsing the software product into code sections;
22 selecting at least one code section;
23 augmenting the selected code section to add protection qualities; and
24 repeating the selecting and the augmenting for different code sections until
25 the desired quantity of protection has been applied.

1
2 **19.** A method as recited in claim 18, wherein the establishing comprises
3 enabling a user to enter the parameters.
4

5 **20.** A method as recited in claim 18, wherein the augmenting comprises
6 applying a protection technique selected from a group of protection techniques
7 comprising code integrity verification, acyclic code integrity verification, cyclic
8 code integrity verification, secret key scattering, obfuscated function execution,
9 encryption/decryption, probabilistic checking, Boolean check obfuscation, in-
10 lining, reseeding pseudo random number generators with time varying inputs, anti-
11 disassembly methods, varying execution paths between runs, anti-debugging
12 methods, and time/space separation between tamper detection and response.
13

14 **21.** A method as recited in claim 18, wherein the augmenting comprises
15 applying a protection technique in which a checksum can be computed on a set of
16 bytes of the digital good without actually reading the bytes.
17

18 **22.** A computer-readable medium comprising computer-readable
19 instructions that, when executed by a processor, direct a computer system to
20 perform the method as recited in claim 18.
21

22 **23.** A production system, comprising:
23 a memory to store an original digital good; and
24 a production server equipped with a set of multiple protection tools that
25 may be used to augment the original digital good for protection purposes, the

1 production server being configured to parse the original digital good and apply
2 protection tools selected from the set of protection tools to various portions of the
3 original digital good in a random manner to produce a protected digital good
4 having a composite of variously protected portions.

5
6 **24.** A production system as recited in claim 23, wherein the protection
7 tools are selected from a group of protection tools comprising code integrity
8 verification, acyclic code integrity verification, cyclic code integrity verification,
9 secret key scattering, obfuscated function execution, encryption/decryption,
10 probabilistic checking, Boolean check obfuscation, in-lining, reseeding pseudo
11 random number generators with time varying inputs, anti-disassembly methods,
12 varying execution paths between runs, anti-debugging methods, and time/space
13 separation between tamper detection and response.

14
15 **25.** A production system as recited in claim 23, wherein the production
16 server applies a protection tool that enables a checksum to be computed on a set of
17 bytes of the digital good without actually reading the bytes.

18
19 **26.** A production system as recited in claim 23, wherein the production
20 server has a pseudo random generator to introduce randomness into the application
21 of the protection tools to various portions of the original digital good.

22
23 **27.** An obfuscation system, comprising:
24 a parser to parse a digital good into a plurality of segments;
25

1 a set of protection tools that may be applied to the segments of the digital
2 good to augment the segments with protection qualities;

3 a target segment selector to select at least one segment from the plurality of
4 segments; and

5 a tool selector to select at least one protection tool from the set of protection
6 tools and apply the selected protection tool to the selected segment.

7
8 **28.** An obfuscation system as recited in claim 27, wherein the protection
9 tools are selected from a group of protection tools comprising code integrity
10 verification, acyclic code integrity verification, cyclic code integrity verification,
11 secret key scattering, obfuscated function execution, encryption/decryption,
12 probabilistic checking, Boolean check obfuscation, in-lining, reseeding pseudo
13 random number generators with time varying inputs, anti-disassembly methods,
14 varying execution paths between runs, anti-debugging methods, and time/space
15 separation between tamper detection and response.

16
17 **29.** An obfuscation system as recited in claim 27, wherein the target
18 segment selector comprises a pseudo random generator to enable random selection
19 of the segment.

20
21 **30.** An obfuscation system as recited in claim 27, wherein the tool
22 selector comprises a pseudo random generator to enable random selection of the
23 protection tool.
24
25

1 **31.** An obfuscation system as recited in claim 27, further comprising a
2 quantitative unit to specify a quantity of protection qualities to be added to the
3 digital good.

4
5 **32.** A client-server system, comprising:
6 a production server to randomly apply various forms of protection to a
7 digital good to produce a protected digital good; and
8 a client to store and execute the protected digital good, the client being
9 configured to evaluate the protected digital good to determine whether the
10 protected digital good has been tampered with.

11
12 **33.** One or more computer-readable media having computer-executable
13 instructions that, when executed, direct a computing device to:
14 parse a digital good into a plurality of segments; and
15 apply multiple different protection tools to various segments in a random
16 manner to produce a protected digital good having a composite of variously
17 protected portions.

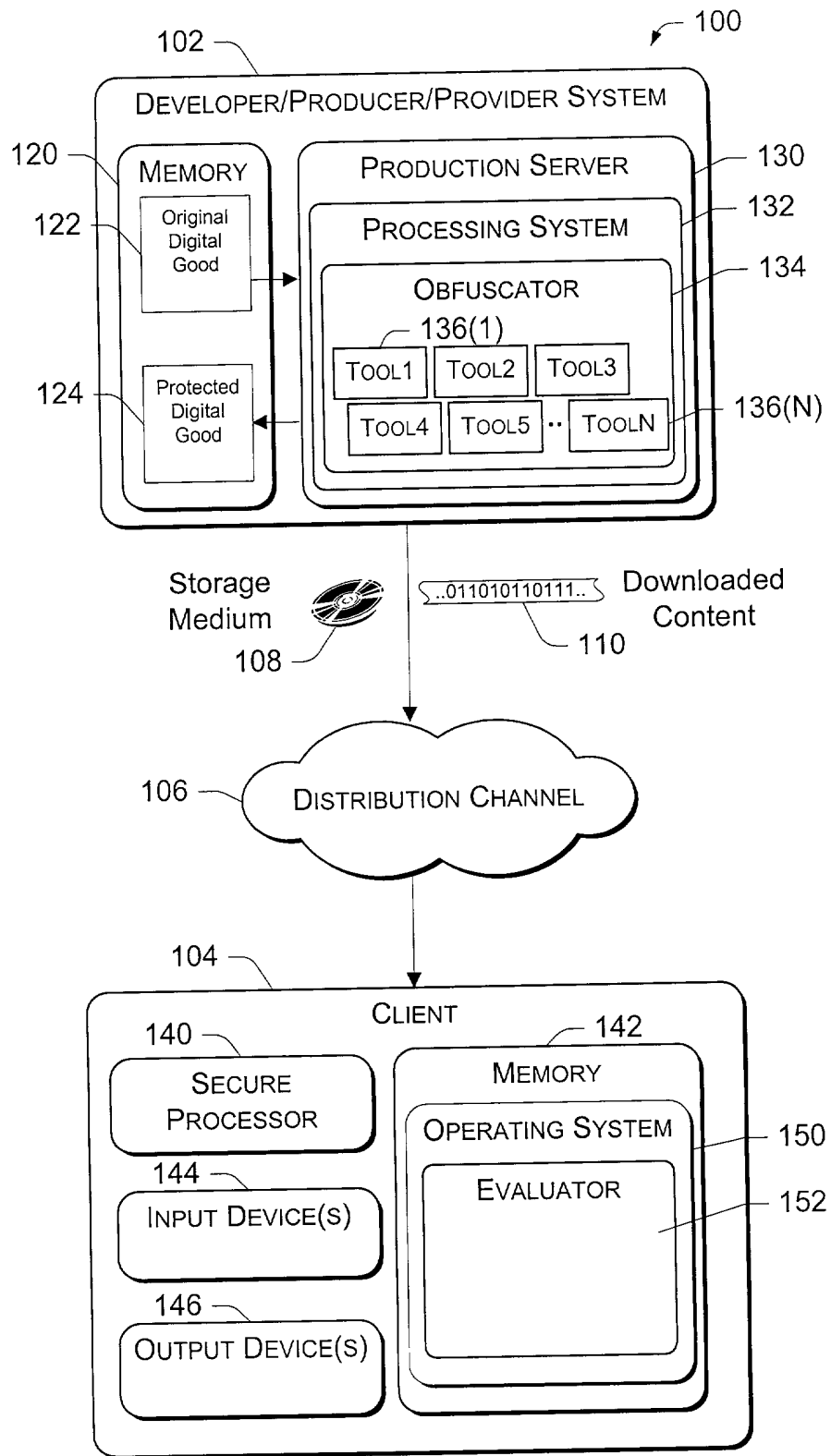
18
19 **34.** One or more computer-readable media as recited in claim 33, further
20 comprising computer-executable instructions to randomly select the protection
21 tools from a set of available protection tools.

1 **35.** One or more computer-readable media as recited in claim 33,
2 further comprising computer-executable instructions to apply the protection tools
3 to randomly selected portions of the original digital good.

4
5 **36.** One or more computer-readable media as recited in claim 33,
6 wherein the protection tools are selected from a group of protection tools
7 comprising code integrity verification, acyclic code integrity verification, cyclic
8 code integrity verification, secret key scattering, obfuscated function execution,
9 encryption/decryption, probabilistic checking, Boolean check obfuscation, in-
10 lining, reseeding pseudo random number generators with time varying inputs, anti-
11 disassembly methods, varying execution paths between runs, anti-debugging
12 methods, and time/space separation between tamper detection and response.
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1 **ABSTRACT**

2 A digital rights management (DRM) distribution architecture produces and
3 distributes digital goods (e.g., software, audio, video, and other content) in a
4 fashion that renders the digital goods resistant to many known forms of attacks.
5 The DRM distribution architecture protects digital goods by automatically and
6 randomly manipulating portions of the code using multiple protection techniques.
7 Applying a mixture protection techniques in random fashion makes it extremely
8 difficult for pirates to create illicit copies that go undetected as legitimate copies.
9 In addition, the architecture also supports a quantitative unit that allows a producer
10 to specify how much protection may be added to the digital good.
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*Fig. 1*

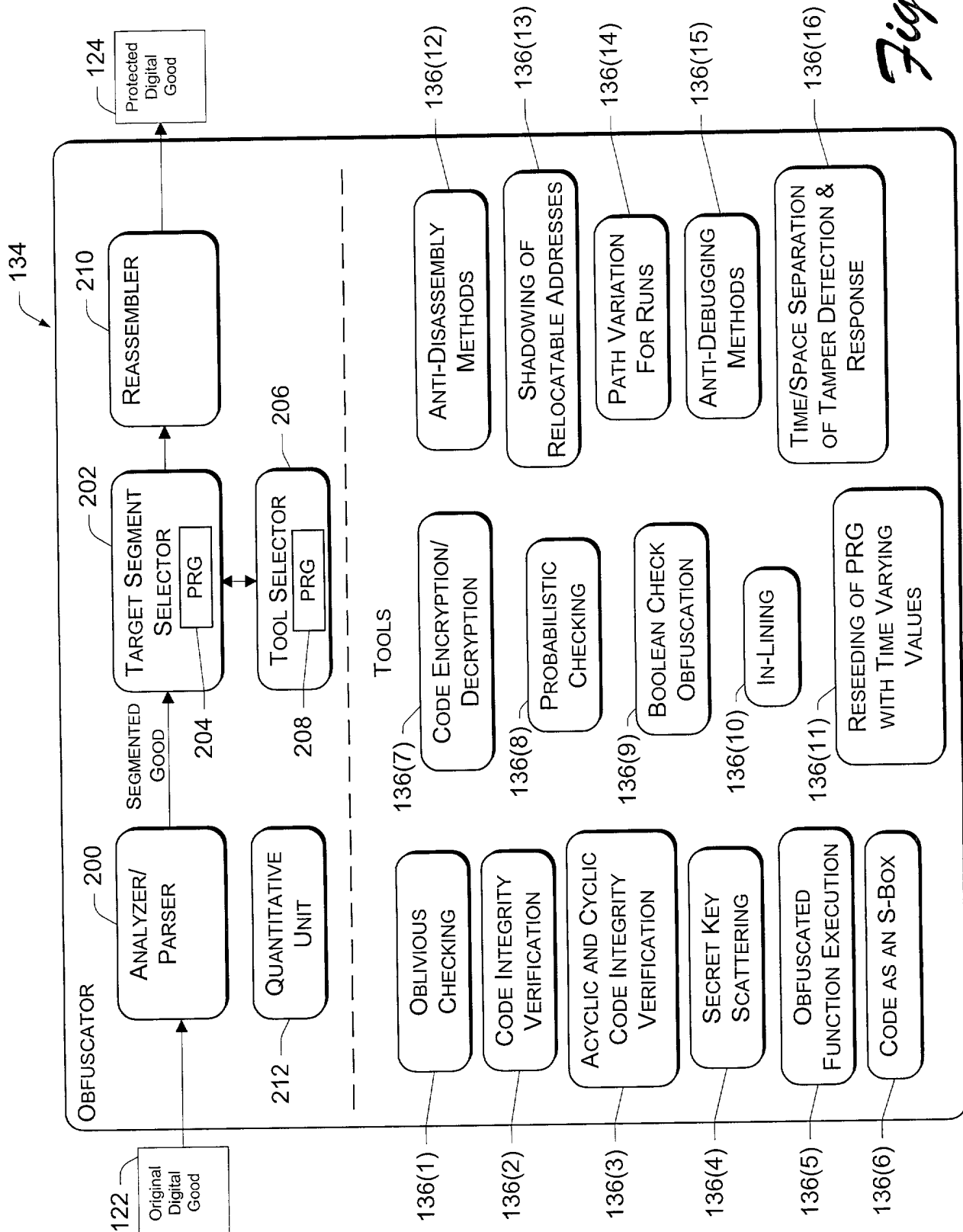
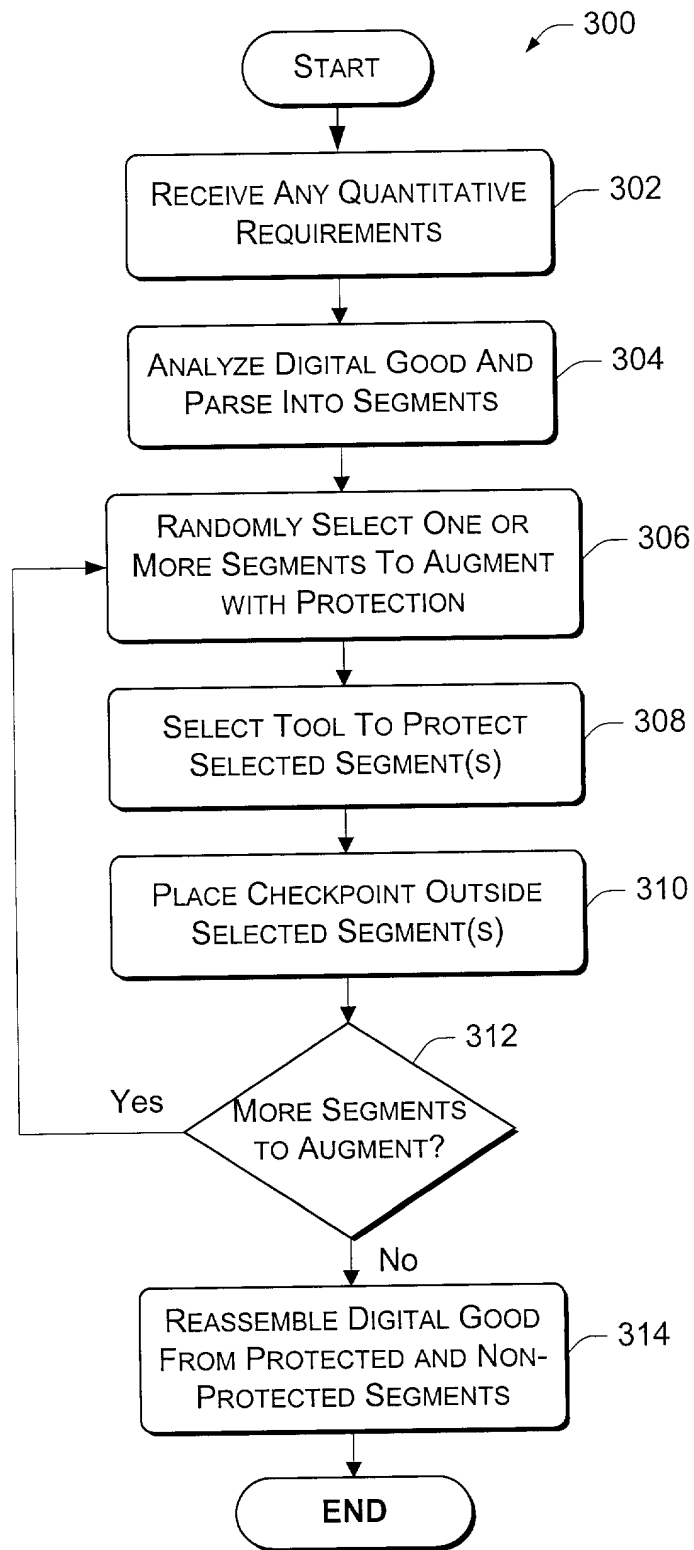


Fig. 2

*Fig. 3*

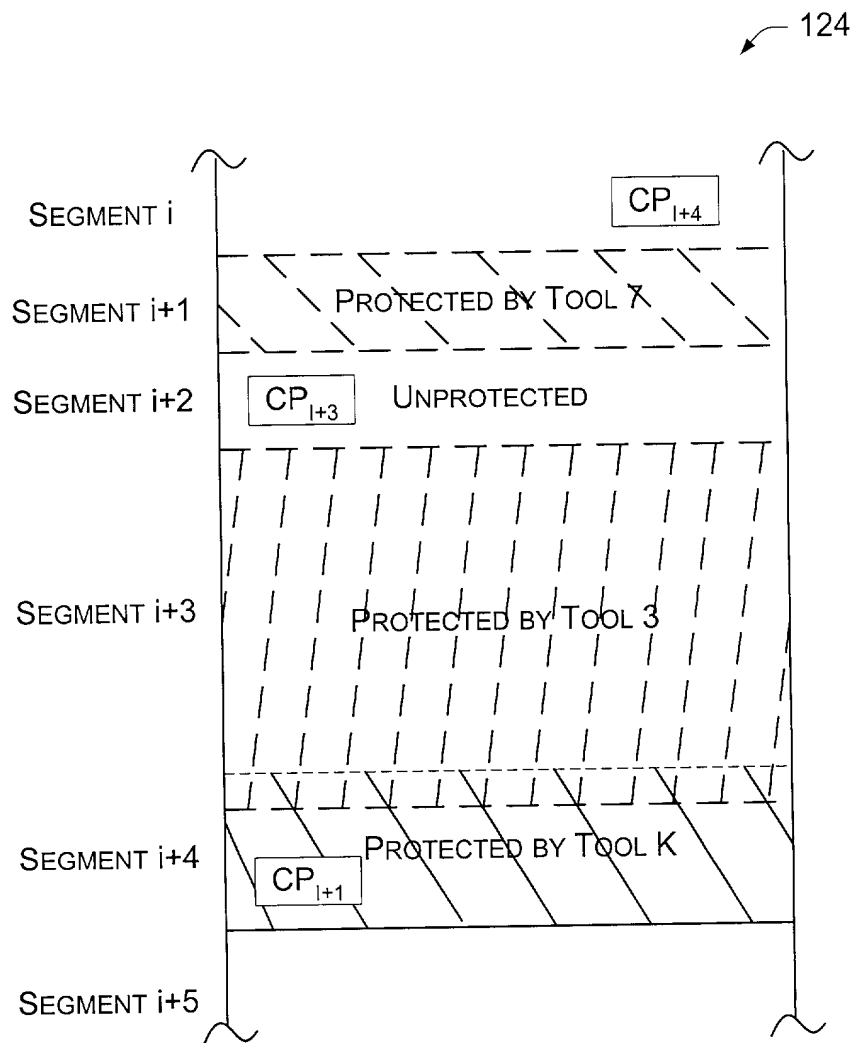
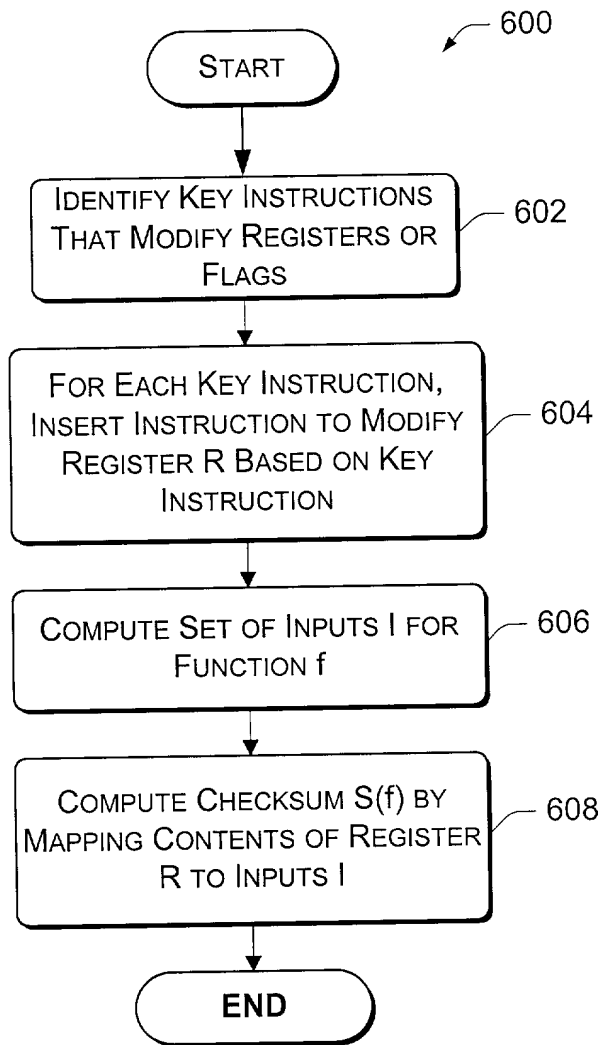
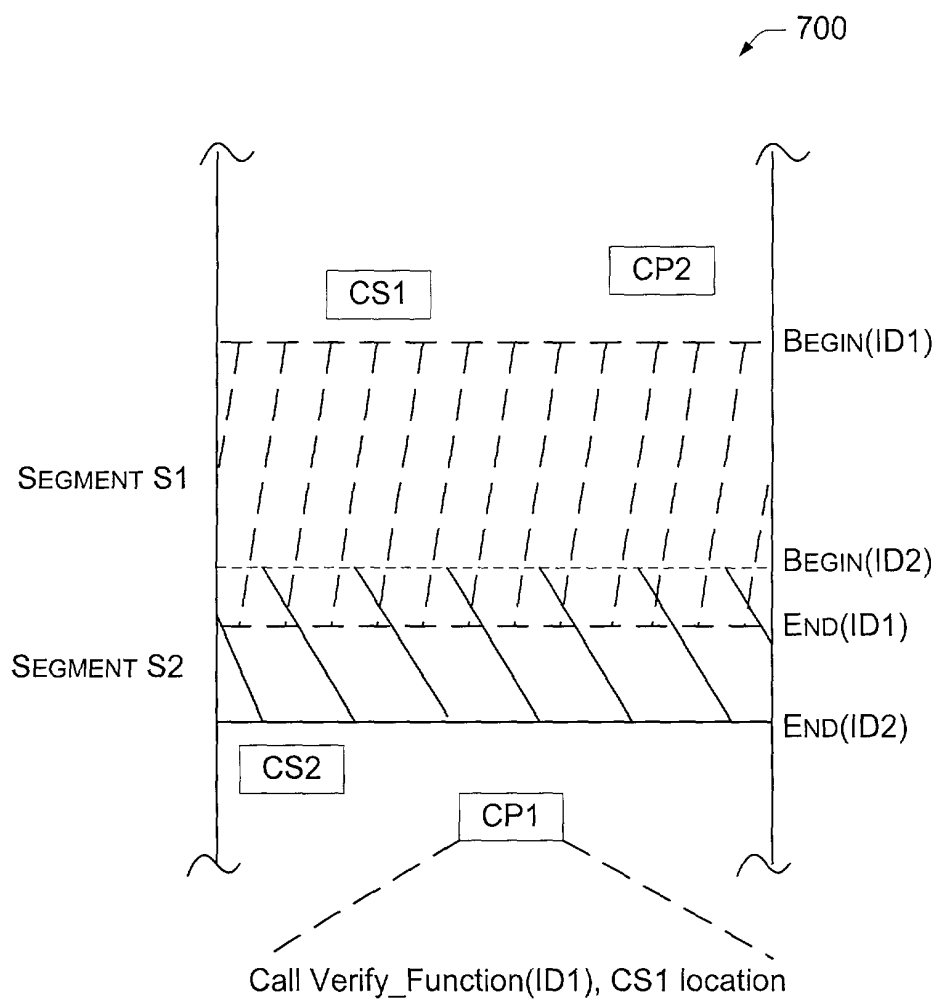
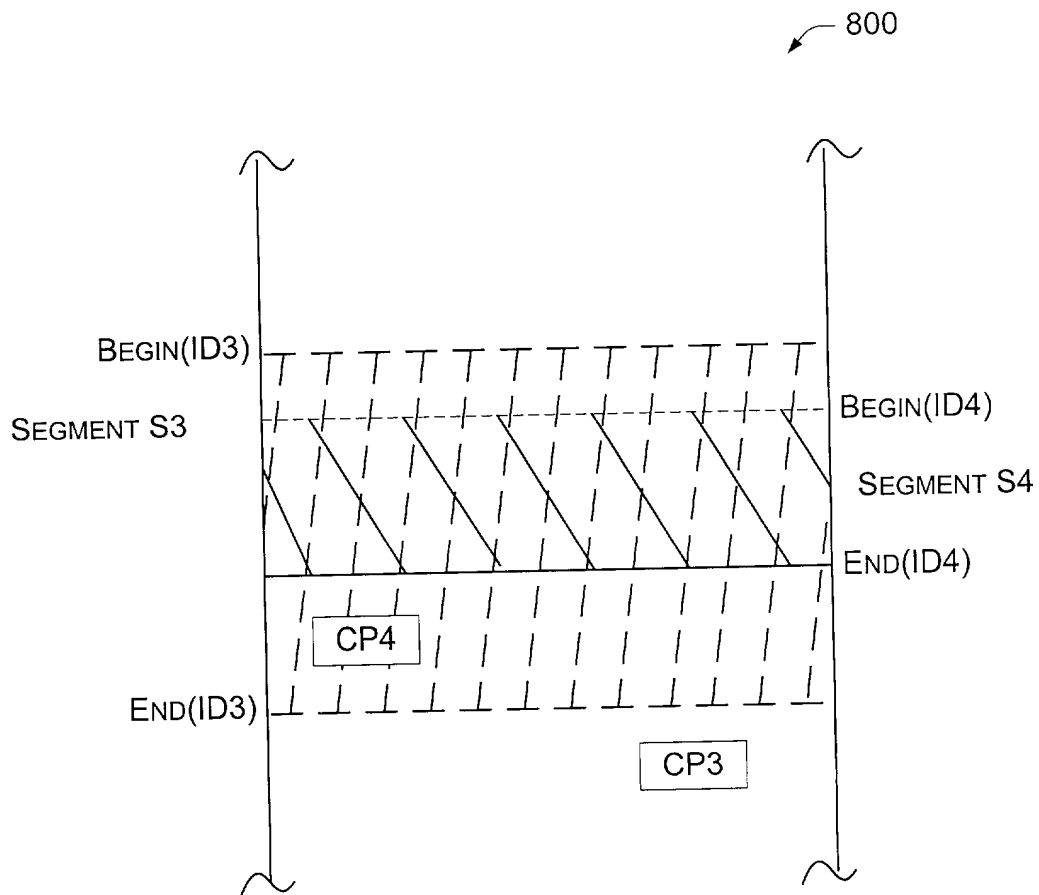
*Fig. 4*



Fig. 5

*Fig. 6*

*Fig. 7*

*Fig. 8*